APS Upgrade Accelerator Systems

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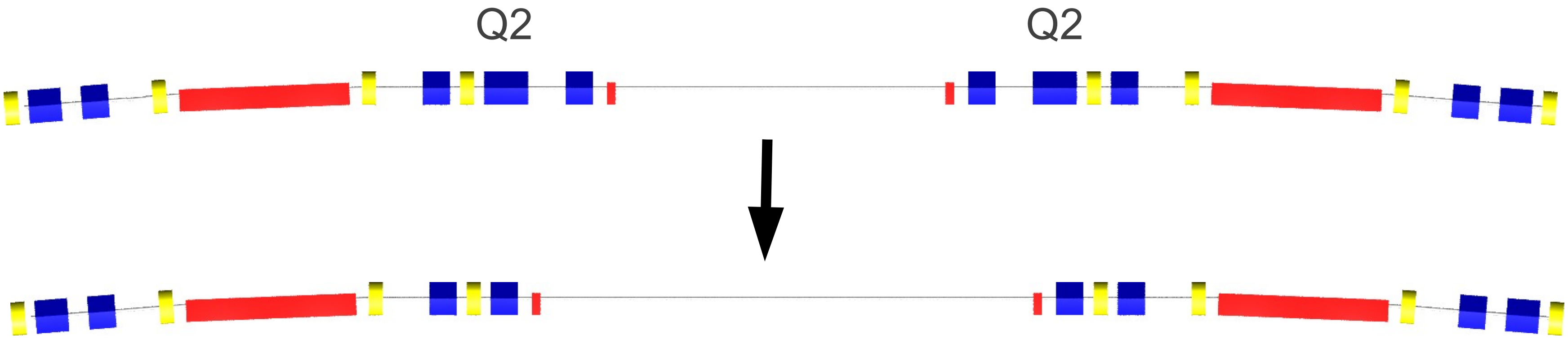
APS Scientific Advisory Committee
October 29, 2010

Overview of Accelerator Upgrades

- Strive for no significant negative impacts on performance
- Increase capacity
  - More canted straights
  - Several long straights
- Improve beam stability to support more demanding experiments
  - Goal is a 2~4-fold improvement
- Increase brightness and flux for 25~100 keV
  - Optimized insertion devices, including SC undulators
  - 150 mA with 200 mA option
    - Front ends and beamlines will be 200-mA capable
  - Improved coupling control
- Enhance timing experiments
  - Provide high-rate short x-ray pulses (now 50~100 ps FWHM)
  - Retain existing fill patterns at higher current

Long straight section (LSS) scheme

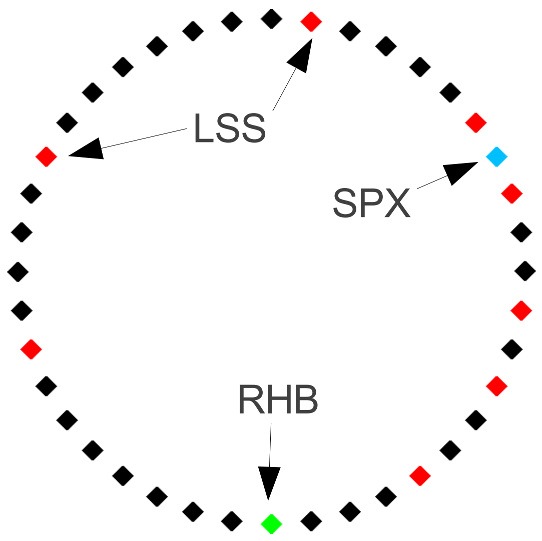
- LSS can be implemented at APS with a simple scheme
  - Remove the Q2 magnets on either side of SS
  - Remove the adjacent correctors
  - Remove the adjacent BPMs
  - Slide other components away from the ID



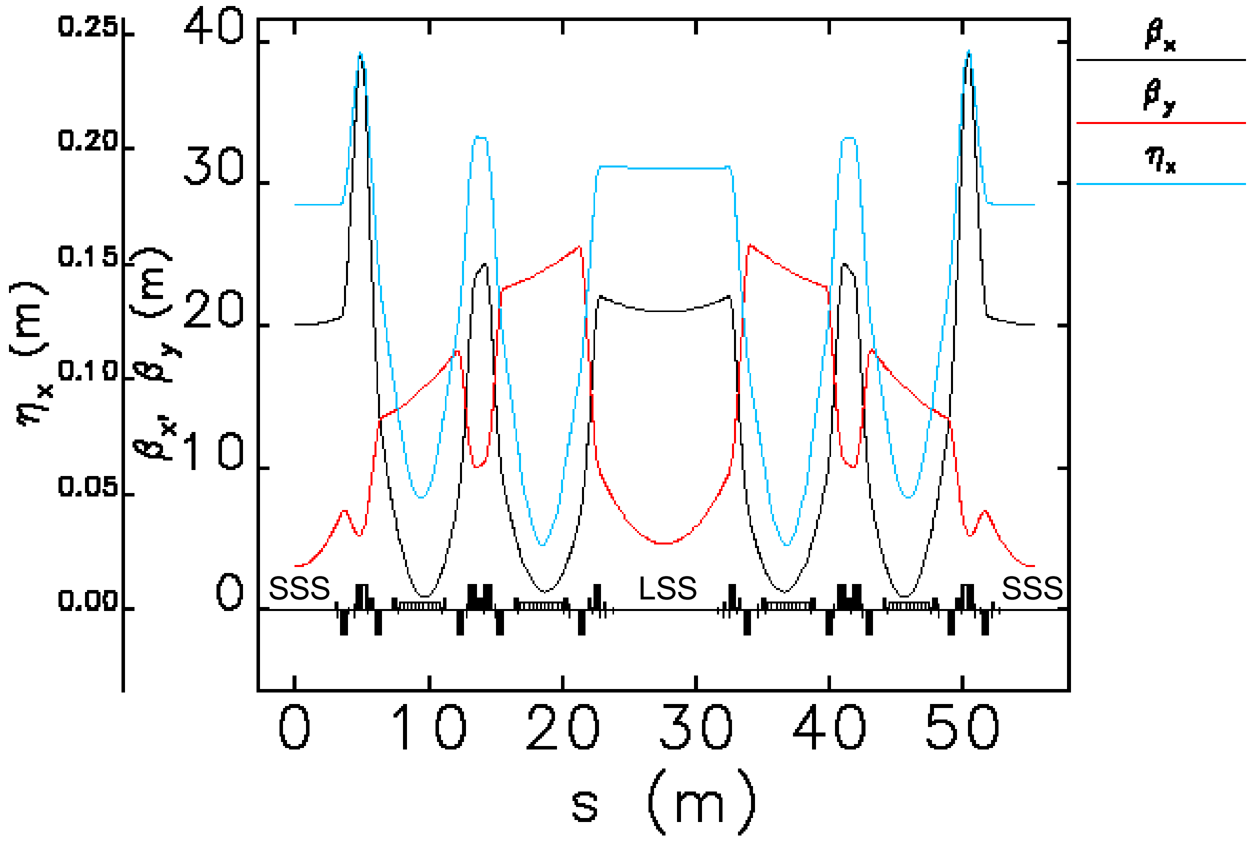
- Increases space available for ID from 4.8 to 7.7m
- Most cost-effective option for LSS
- Can use existing spare magnets for installation

LSS Placement

- Traditionally, only symmetric arrangements considered viable
  - Easier to obtain large injection aperture and lifetime
  - Increases cost by requiring experimental programs to move
- Multi-objective genetic algorithms used to develop lattices with reduced symmetry, directly tuning for
  - Large Touschek lifetime
  - Large dynamic aperture
  - Adequate chromaticity
- Variables include tunes and 25~50 sextupoles
- APS and ANL computing resources (fusion, intrepid) invaluable
- Have developed three basic lattices:
  - 8 “random” LSS
  - 8RLSS + SPX in sector 7
  - 8RLSS + SPX + RHB in sector 20

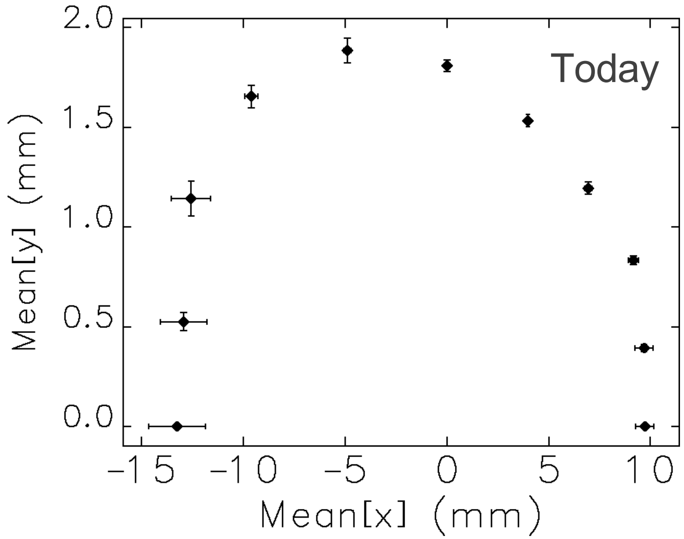


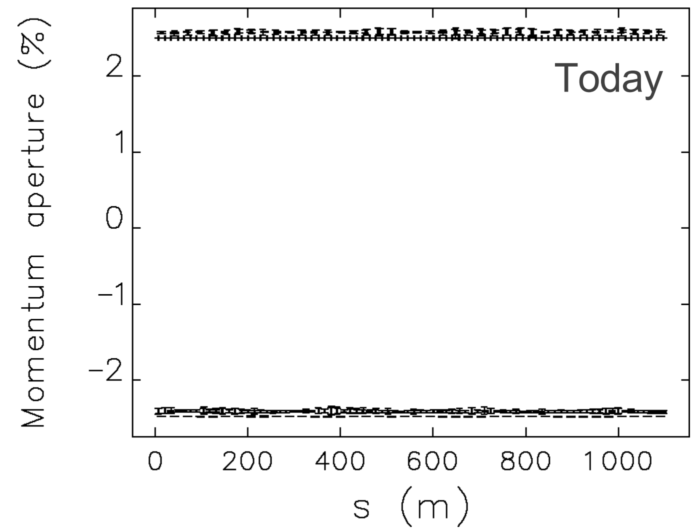
LSS Lattice Functions

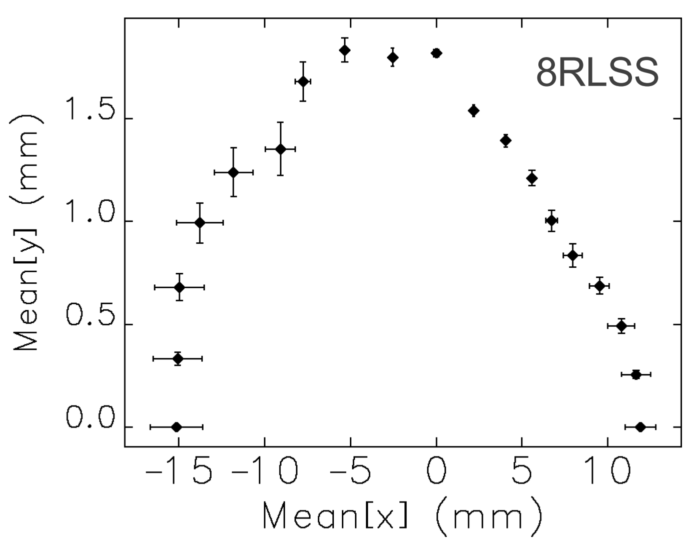


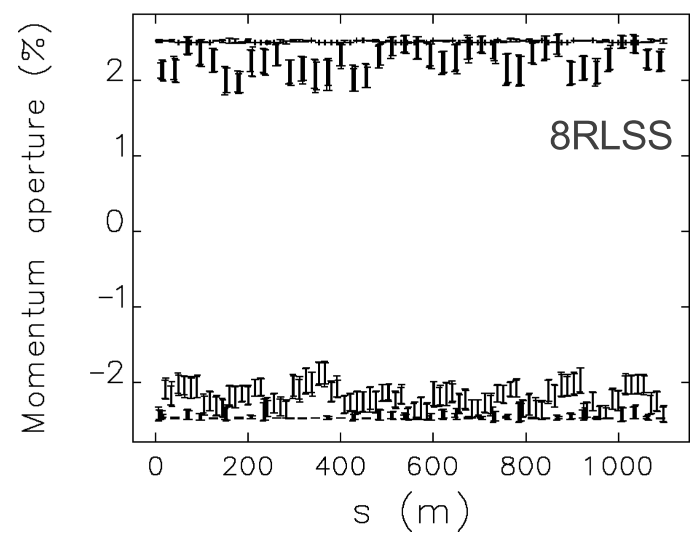
- Horizontal lattice functions are little changed
- Vertical beta function increases from 3m to 5m
- 3.3 nm effective emittance

Comparison with APS Today









Lifetime Predictions (50 Ensembles)

	Now $\xi_{x,y} = 7, 6$ h	8RLSS $\xi = 9$ h	8RLSS+SPX $\xi = 7$ h	8RLSS+SPX+RHB $\xi = 7$ h
100 mA/24				
median	9.2	8.3	8.2	7.4
5^{th} percentile	8.6	6.3	7.1	5.8
200 mA/24				
median	-	5.1	5.0	$\boxed{4.5}$
5^{th} percentile	-	3.8	4.4	$\boxed{3.6}$
16 mA (hybrid)				
median	-	3.3	-	-
5^{th} percentile	-	2.5	-	-
184 mA/56 (hybrid)				
median	-	9.8	-	-
5^{th} percentile	-	7.4	-	-
200 mA/324				
median	35.8	32.7	32.4	29.7
5^{th} percentile	33.7	25.8	28.7	24.3

- Only 8RLSS has sufficient chromaticity for hybrid mode
- 8RLSS+SPX+RHB is marginal for 200 mA
- Work continues on higher-chromaticity solutions

Other “Lattice” Options Explored

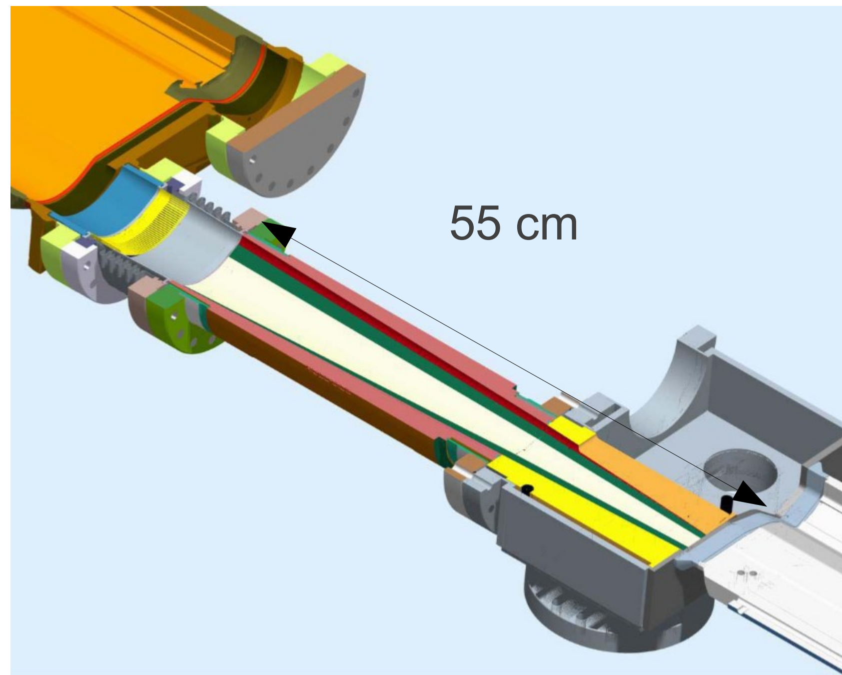
- Higher beam energy
  - Advantageous for ~50 keV and above
  - Detrimental for ~25 keV and below
- Lower beam energy
  - Advantageous for ~25 keV and below…
- Alternating beta functions
- Lower emittance “orbit displacement” scheme
  - ~1.5 nm effective emittance
  - Might be a special operating mode with 324 bunches
- Speculative low emittance schemes, e.g.,
  - ~4 GeV operation with 35 damping wigglers would give 0.2 nm emittance (!)
- These proved less appealing than LSS

Mockup Lattice Testing

- We can test LSS-like lattices using our independent power supplies
  - Turn off Q1 magnets to simulate removing magnets
- Tested 8RLSS mock-up lattice
  - Lattice has normal injection efficiency and lifetime
  - Was essential to steer the beam to the center of the sextupoles
  - Implication: cannot have significant steering of beam to compensate for misaligned beamlines
    - Must realign 37 beamlines (23 IDs and 14 BMs)
    - Probably should start ASAP
- Tested 8RLSS+SPX+RHB mockup lattice
  - Lattice has normal injection efficiency
  - Lifetime is significantly reduced (5 hours at 100 mA)
  - Study of this lattice continues

Long Taper Development

- Impedance model allows prediction of single-bunch limit
- LSSs will increase effective vertical impedance
  - Longer chamber and larger beta functions
  - Single bunch limit 16 mA → 12 mA
  - Exacerbated by problems obtaining very high chromaticities
- Longer (linear) tapers will reduce impedance
- Tapers will use “accelerator real estate”
- APS-U involves replacing tapers at LSS, plus small gap chamber at 4ID
- Also considering copper- or silver-coating of chambers

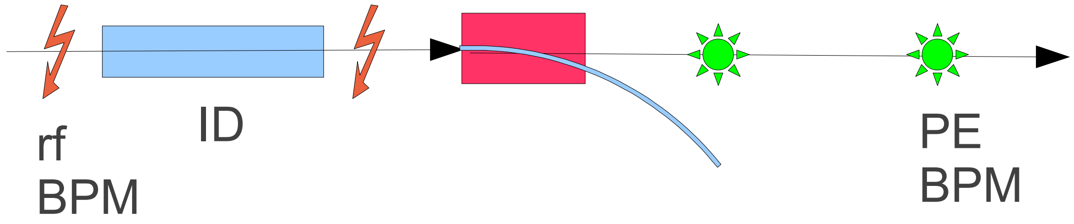


Beam Stabilization

- APS has fallen behind in beam stability
  - Better stability is like a brightness upgrade
  - Targeting a two- to four-fold improvement
- Components of beam stability upgrade
  - New BPM electronics
  - Storage ring vacuum chamber microwave mode dampers
  - Real-time feedback system upgrade
  - Front-end hard x-ray beam position monitor developments
  - Tunnel temperature regulation
  - BPM position sensing

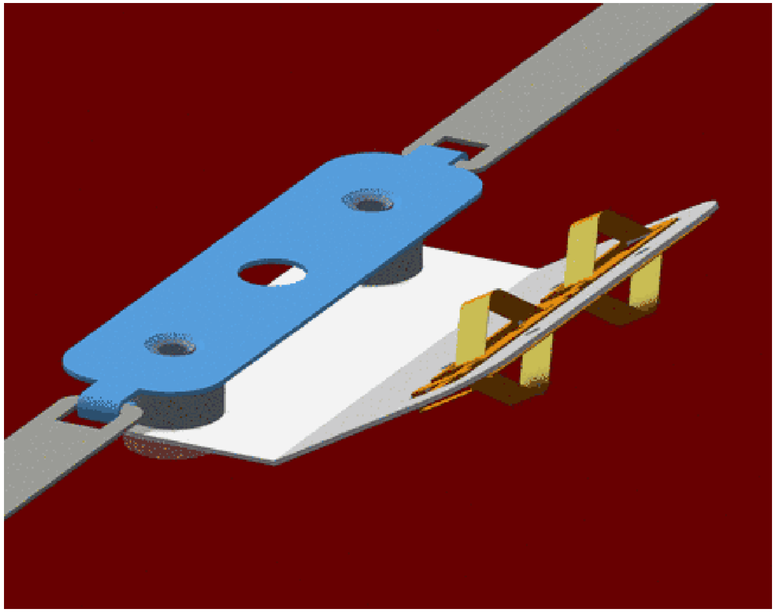
		AC rms Motion, 0.1-200 Hz		**Long-term drift (One Week)**	
		μm rms	μrad rms	μm rms	μrad rms
Horizontal	Present	5.0	0.85	7.0	1.4
	Upgrade	3.0	0.53	5.0	1.0
Vertical	Present	1.6	0.80	5.0	2.5
	Upgrade	0.42	0.22	1.0	0.5

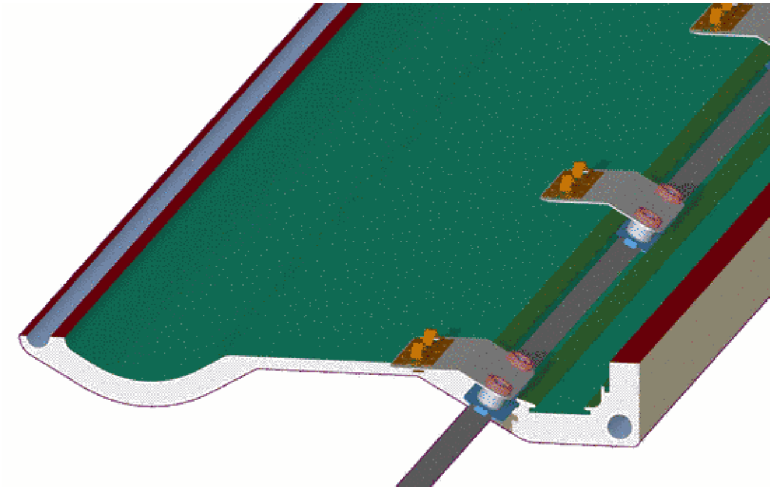
New BPM Electronics for ID Beam Control



- Will upgrade electronics to reduce
  - AC noise floor
  - Long-term drift
- Options
  - APS-design BSP-100 module
  - Libera units (commercial)
  - NSLS-II BPM electronics
- Scope:
  - 70+ rf BPMs (need three for each canted straight)
  - 70 photon BPMs
- Benefit:
  - Two-fold reduction in AC noise floor

Chamber Mode Dampers





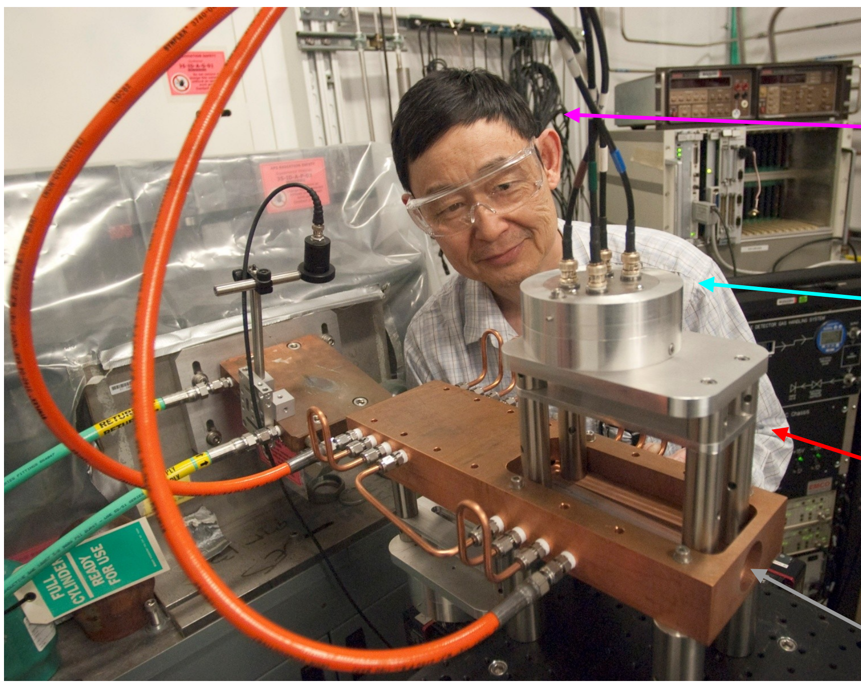
- RF modes in large-aperture chambers corrupt BPM signals
- These devices effectively short out those modes
- Scope: slide into unused NEG strip slots in 200 chambers
- Benefit: doubles the number of available vertical BPMs for feedback
- Recently tested, appears to work as expected

Real-time feedback system upgrade

- Originally commissioned in 1997
- Limited to 1.5 kHz sample rate ⇒ 60 Hz closed-loop bandwidth
- Scope:
  - Complete replacement of existing DSPs & reflective memory system
  - Double the number of BPMs interfaced to the system
  - Double the number of fast steering correctors (relocate and interface to existing correctors)
- Benefits:
  - Increase closed-loop bandwidth to 200 Hz
  - Improve AC stability four-fold
  - Improve feedforward system that mitigates top-up disturbance

Hard X-ray BPM (GRID XBPM)

- Photo-emission BPMs have residual 10~20 micron gap-dependent errors
- X-ray fluorescence is immune to soft bending magnet radiation background
- Major challenge is high power density
- In-air prototype under test at 35ID



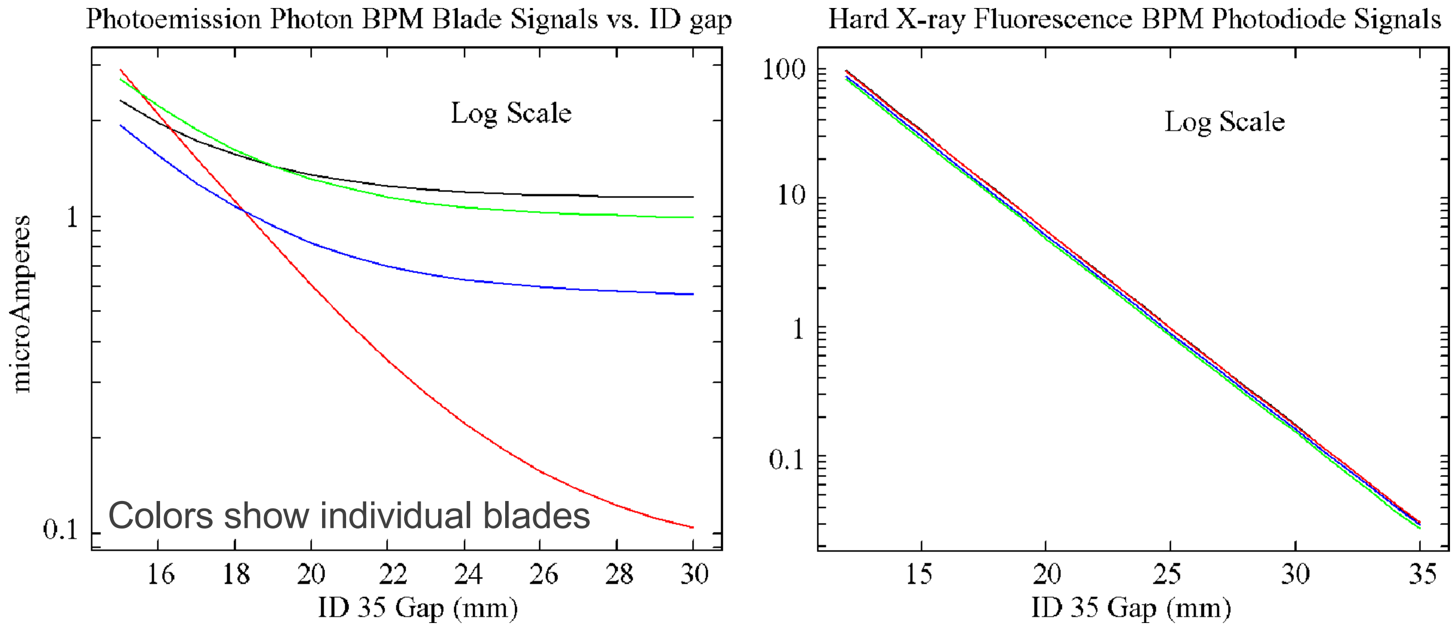
Bingxin Yang

Four Pin diodes (Two sets, top and bottom)

Pinhole "camera" apertures

X-rays

GRID XBPM Tests

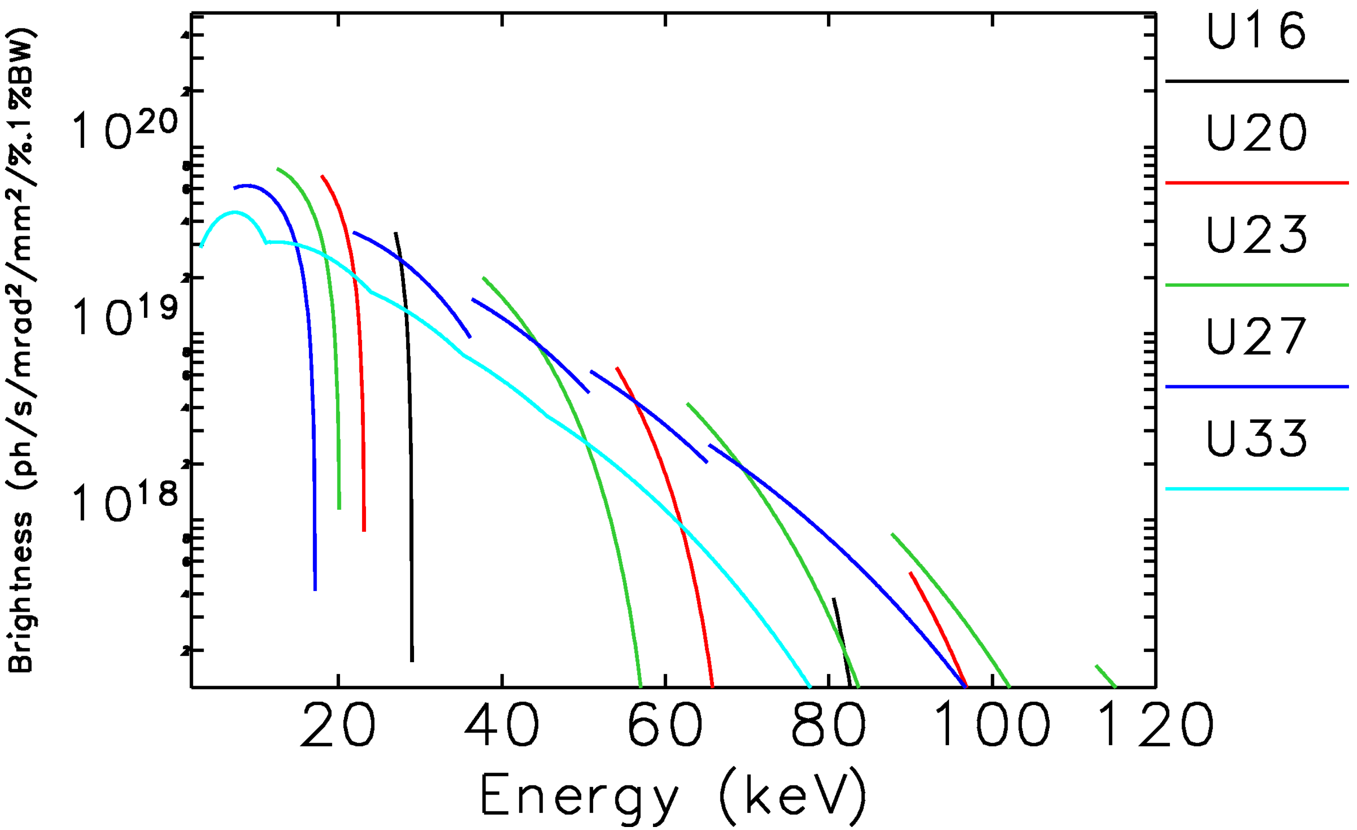


- Photo-emission BPMs see BM background, giving 10~20 micron gap-dependent variation
- GRID XBPM eliminates this issue
- Scope: Install one GRID XBPM in each ID front end (34 total) as part of FE upgrade
- Benefit: two-fold improvement in long-term stability

Undulator Types (Partial List)

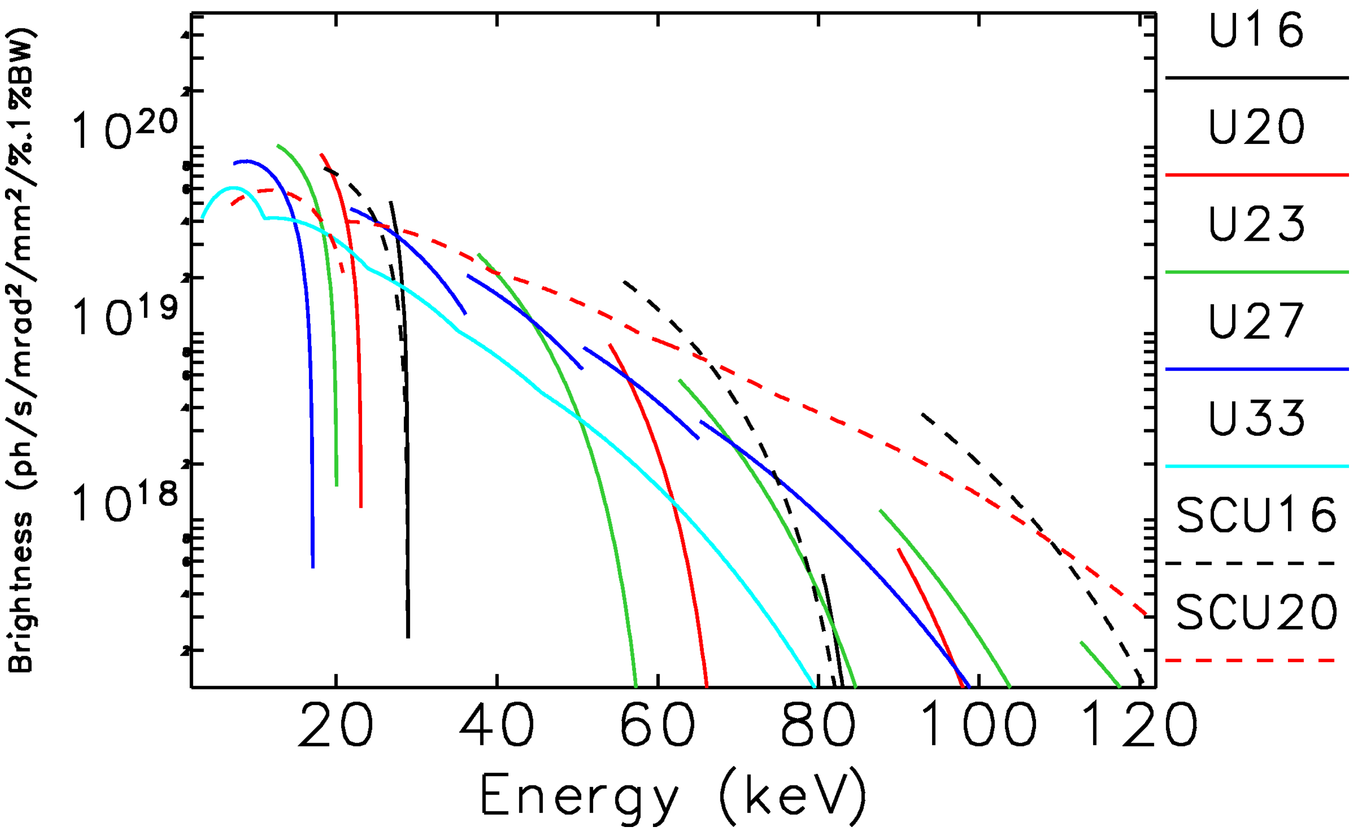
Type	Status	Special features	Issues	# APS-U
Planar HPM	Many in use at APS	Established technology	Min. gap limited by chamber	16
Planar revolver HPM	In use elsewhere	On-line selection of periods	Challenging for longer devices, longer periods	?
Planar in-vacuum HPM	In use elsewhere	Shorter periods, smaller gaps	Large beam impedance	0
SC planar	APS-U R&D	Shorter periods, high brightness	See below	3
APPLE	In use elsewhere	Pol. control, harm. suppress., on-axis heat load suppress.	Non-linear beam dynamics	2
IEX undulator	In devel. (non APS-U R&D)	Pol. control, harm. suppress., on-axis heat load suppress., low energy photons	Non-linear beam dynamics	1

Present Performance (100mA) with Planar Undulators



- HPM devices, 2.4 m long, 10.75 mm gap
- All curves respect original APS front end limits
- Hypothetical U16 and U20 based on design fit.

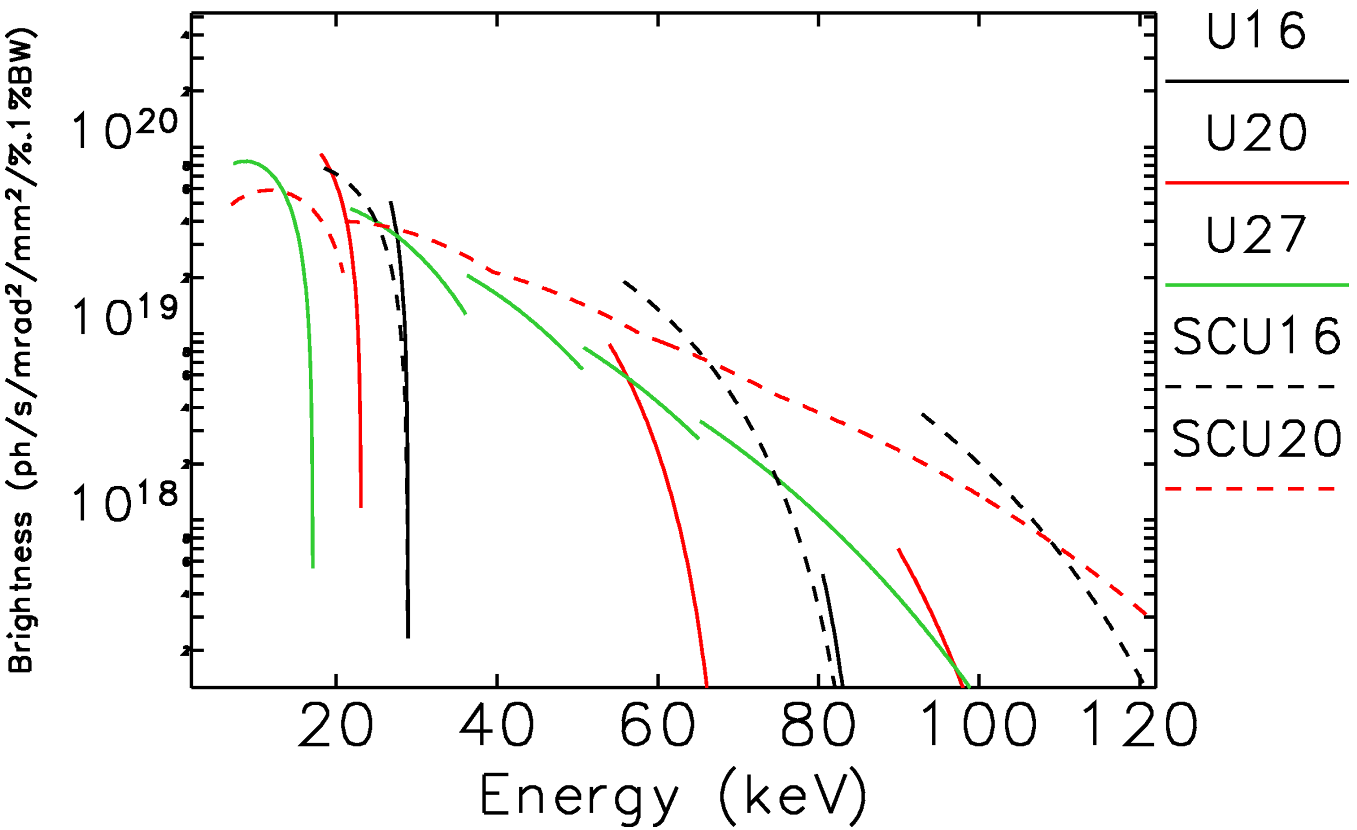
APS-U Performance at 150 mA, Canted SSS



- HPM devices: 2.1 m long, 10.75 mm gap
- SCU devices: 1.2 m long, 9.0 mm gap
- All curves respect canted front end limits

Same overall length

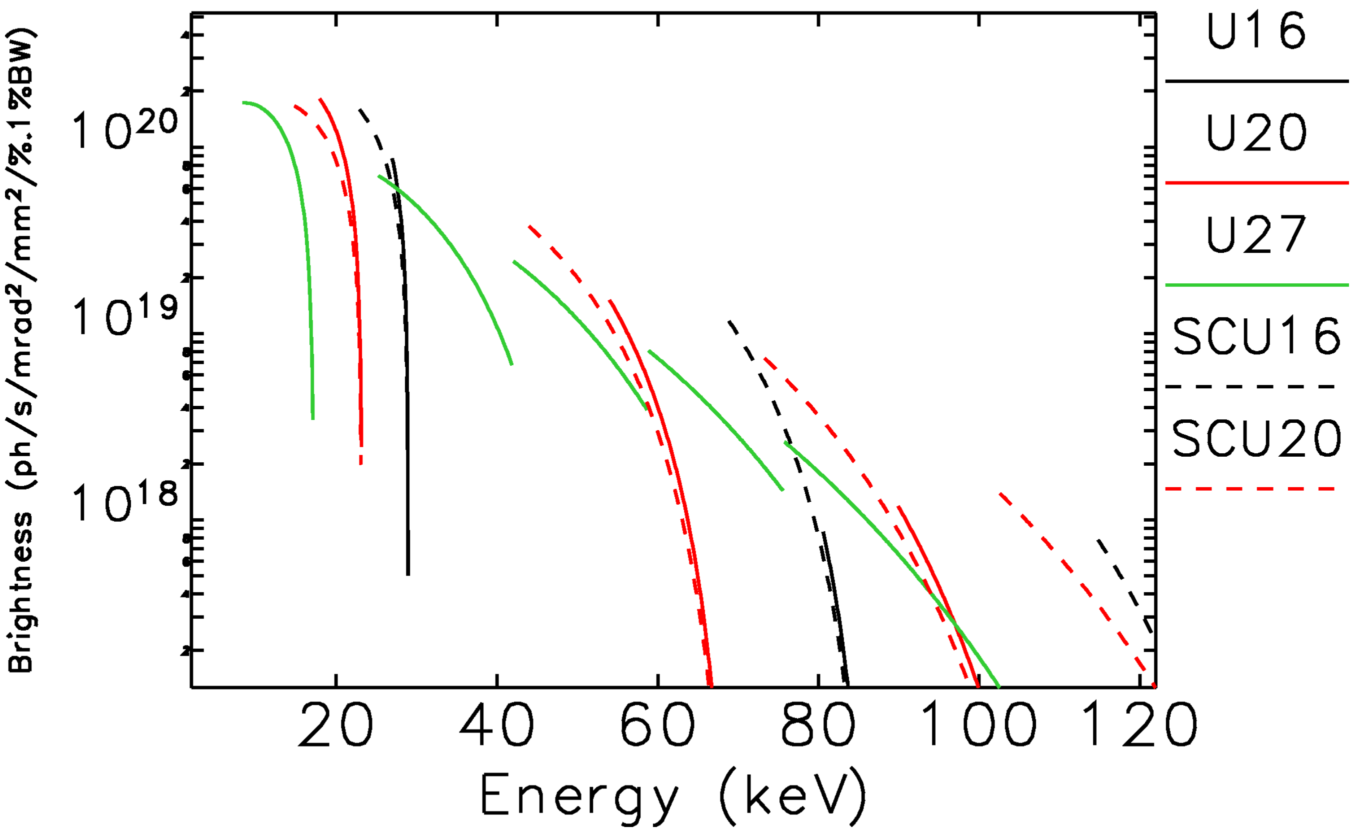
APS-U Performance at 150 mA, Canted SSS



- HPM devices: 2.1 m long, 10.75 mm gap
- SCU devices: 1.2 m long, 9.0 mm gap
- All curves respect canted front end limits

Same overall length

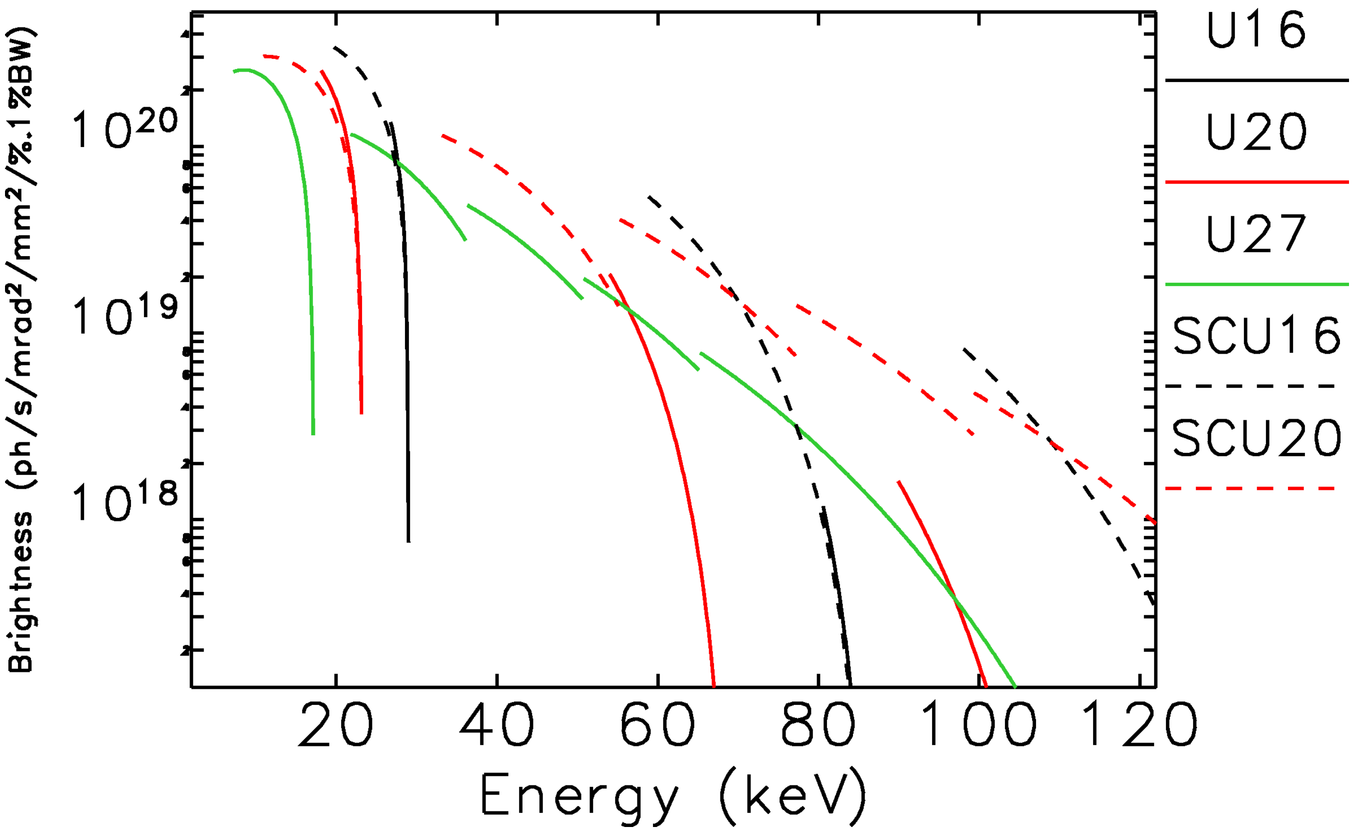
APS-U Performance at 150 mA, Canted LSS



- HPM devices: 3.5 m long, 10.75 mm gap
- SCU devices 2.6 m long, 9.0 mm gap
- All curves respect canted front end limits

Same overall length

APS-U Performance at 150 mA, SSS, HHL

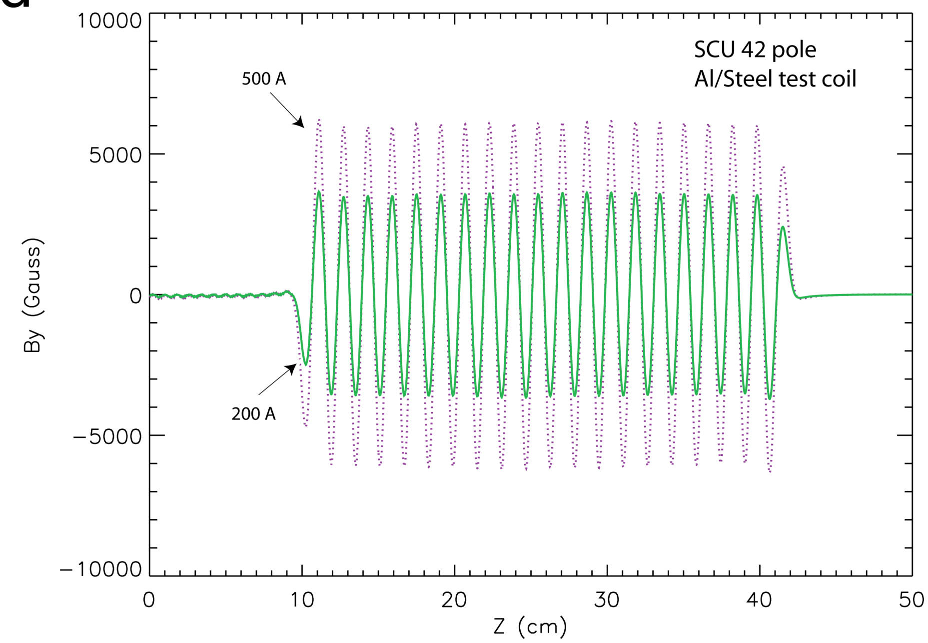


- HPM devices: 4.8 m long, 10.75 mm gap
- SCU devices 3.9 m long, 9.0 mm gap
- All curves respect HHL end limits

Same overall length

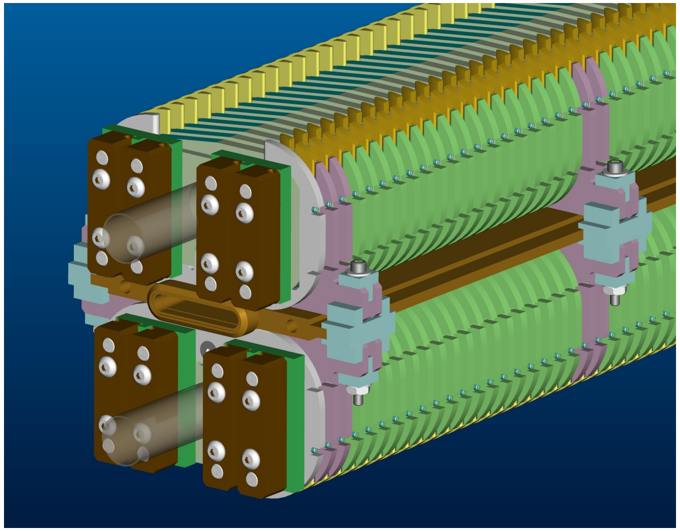
SCU Status

- Prototyping 16mm period device with NbTi wire
  - Targeting 20~25 keV first harmonic
- 42-pole test assemblies manufactured and tested
- Quench at ~700 A
- Design field of 0.61 T reached for 500 A current
  - Gives 20.5 keV
- Rms phase error only 5 deg w/o shimming
  - Comparable to HPM devices
  - Gives good performance for 3rd and 5th harmonics



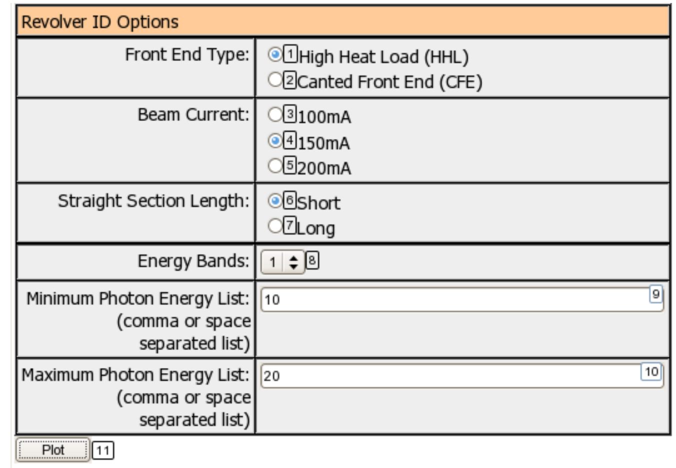
R&D Plan for SCU

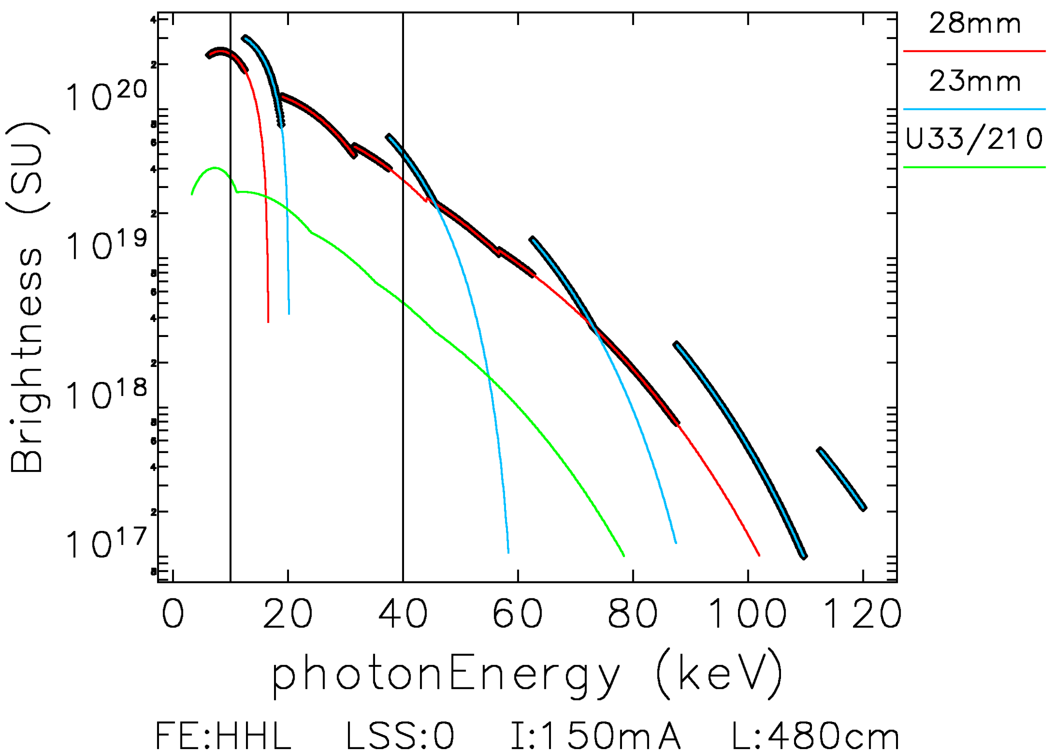
- A short prototype (SCU0) will be installed to answer critical issues
- Measurement of beam-induced heating in various operation modes
- Validation of cryogenic design concept
- Development and verification of methods for building and tuning devices to achieve required field quality
- Development of required magnetic measurement techniques
- Characterization of long-term stability
- Investigation of operational issues, e.g., effect of SCU quench on ring operation, effect of beam strike



Revolver IDs

- Web application developed to make optimized choices of revolver ID periods

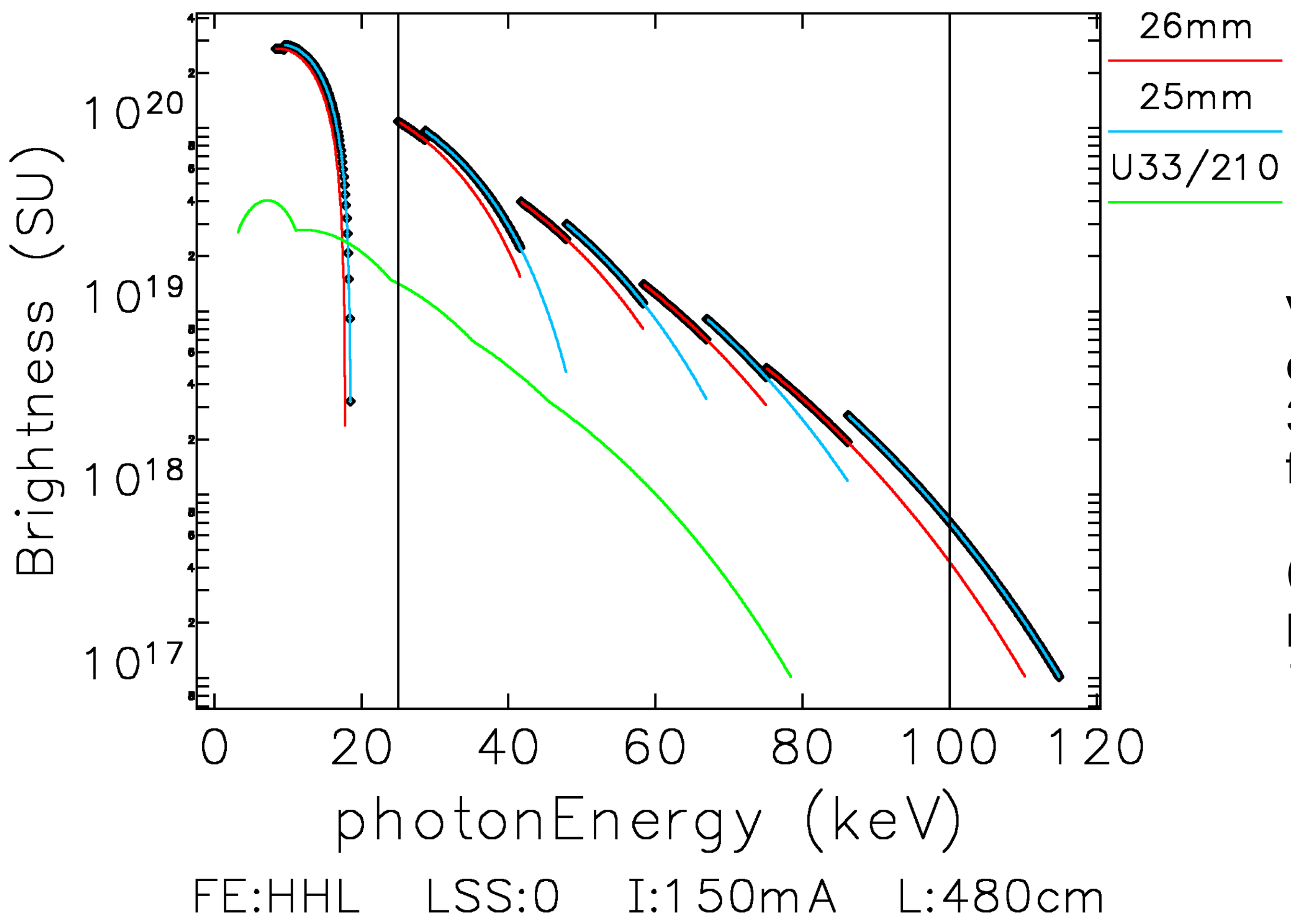




Example of optimized revolver choice for working between 10 and 40 keV at 150 mA with HHL FE and a speculative 480-cm-long insertion device

(U33 curve is for present APS at 100 mA)

Revolver for 25-to-100 keV



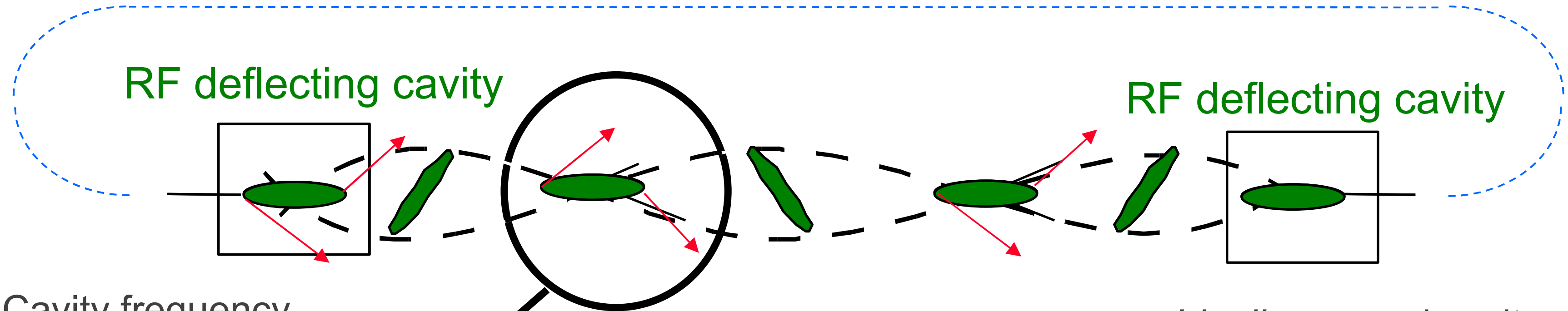
Very good, but not competitive with 3.9-m SCU20 over full range.

(U33 curve is for present APS at 100 mA)

Short-Pulse X-rays (SPX)

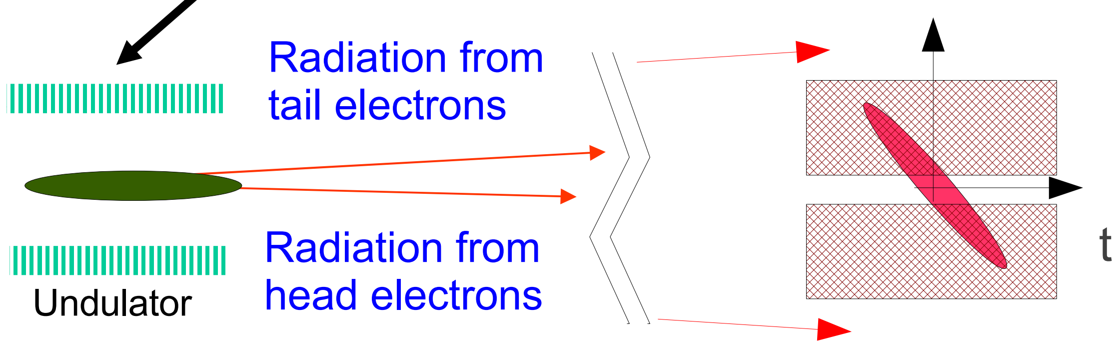
- One important component of the upgrade is to provide short-pulse x-rays
  - Addresses a weakness of storage rings and an area of significant interest
- Several possible schemes
  - Superconducting deflecting cavities
  - Laser slicing
  - “Low alpha” operation
  - Rf phase modulation
  - Harmonic cavity
- Only the first two are really viable
  - Compatible with normal APS operations at 100+ mA
  - Reach to few ps regime or shorter
- Deflecting cavities preferred: much higher average flux

Zholents' Transverse Rf Chirp Concept[1]



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is n*180 degrees

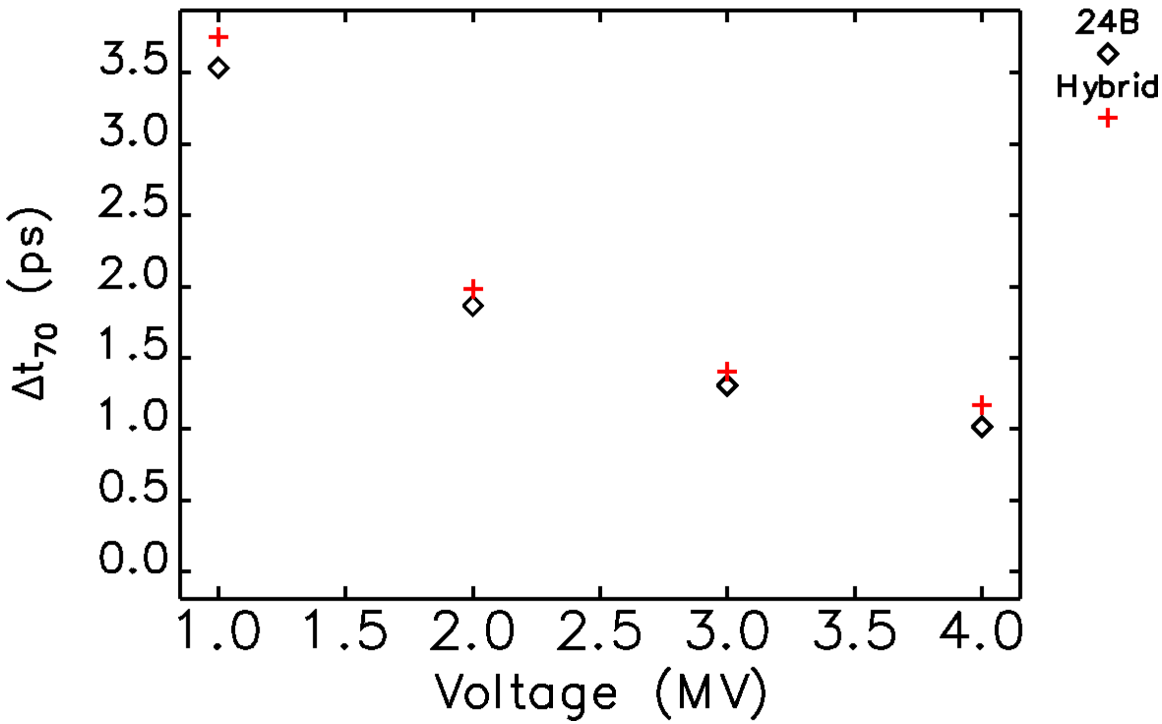


Pulse can be sliced or compressed with asymmetric cut crystal

(Adapted from A. Zholents' August 30, 2004 presentation at APS Strategic Planning Meeting.)

[1] A. Zholents *et al*., NIM A 425, 385 (1999).

Predicted Pulse Duration (10 keV, 2.4-m U33)

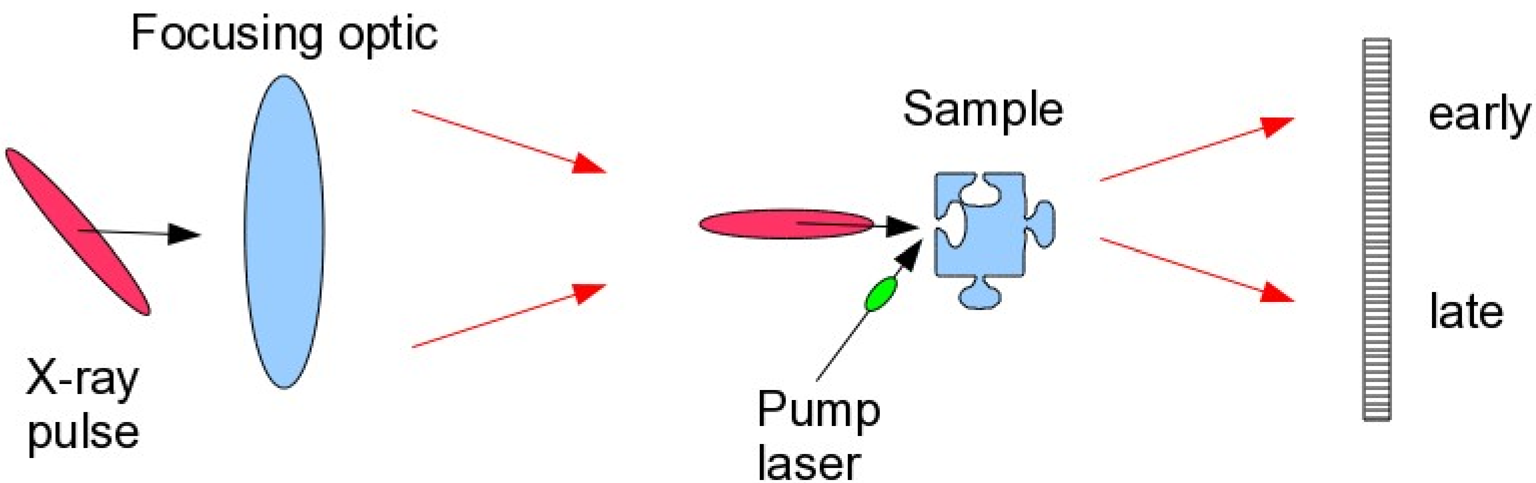


- Assumes slits set for 1% transmission
- Limitations on voltage (related to LSS)
  - 4 MV requires increasing 6ID chamber gap by ~3.5mm[1]
  - 2 MV possible with standard ID chambers

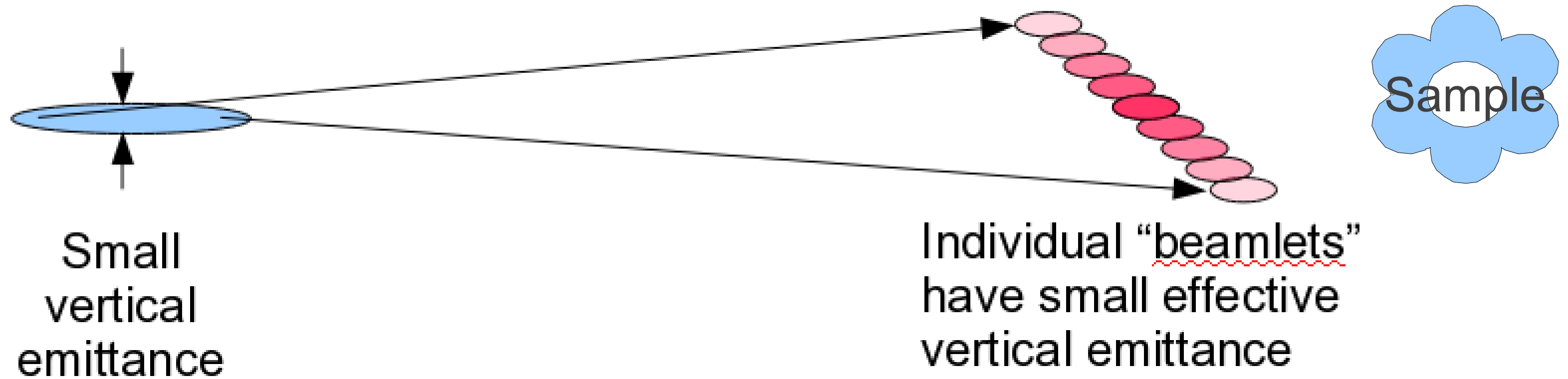
[1]V. Sajaev, AOP-TN-2010-017, 8/16/10.

Other Applications of Chirped Pulses

Spatial encoding of time information in a pump-probe experiment



Coherent imaging with a large vertical spot size



Tolerances from Beam Dynamics Simulations

- Phase and voltage errors in the crab cavities can affect important performance parameters

Specification name	Rms Value	Driving requirement
Common-mode voltage variation	$< 1\%$	Keep intensity and pulse length variation under 1% rms
Common-mode phase variation	$< 4.8^\circ$	Keep intensity variation under 1% rms
Voltage mismatch between cavities	$< 0.5\%$	Keep rms emittance variation under 10% of nominal 35 pm
Phase error between cavities	$< 0.07^\circ$	Keep rms beam motion under 10% of beam size/divergence

- Simulations are for static errors or modulations far from tunes
- Differential phase tolerance particularly challenging
- Tolerances are for 4 MV deflection

Scope of SPX Project

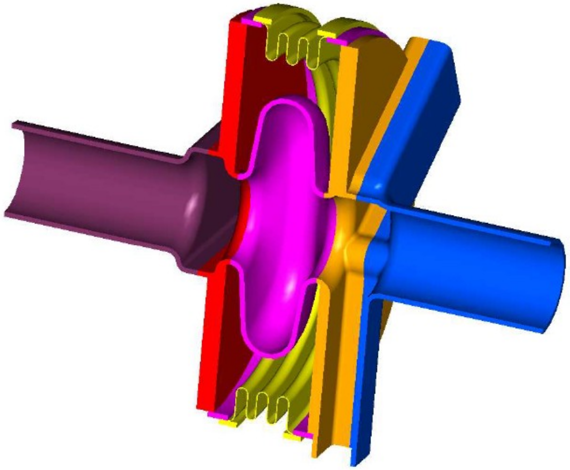
- Two cryomodules, each with 8 SC cavity cells
  - One in, e.g., 6ID upstream, one in 8ID upstream
- Cryoplant for 2K operation of cavities

Quantity	Value
Refrigeration at 2.0 K static+dynamic)	120 W
Refrigeration at 4.5 K(static)	200 W
Thermal shield cooling at 80-90 K (static)	4 kW(LN2)

- High-power rf system delivering ~6.5 kW/cell
  - Possible topologies include one klystron/cell or one klystron/2-cells
- Low-level rf system capable of delivering required stability
- Diagnostics
  - Measure beam tilt inside and outside SPX region
  - Measure beam arrival time
  - Beam loss monitors to protect cavities

SPX R&D Plan

- On-going R&D program covering
  - Lattice development
  - Beam dynamics
  - Collective effects
  - Cavity design including mode damping
  - Cryostat and cryogenic system design
  - LLRF and timing design
  - High-power rf system
  - Diagnostics
- Planning installation in ring of test system
  - Pair of cavities, either in one sector or two
  - Presently defining what risks can be addressed by this
  - Many risks can be addressed by off-line experiments



Higher Current

- Accelerator is presently capable of 150 mA operation in all fill modes
  - Recent tests show that only 2 klystrons are needed
- 200 mA operation is taken as a long-term goal
  - All changes must be 200mA-compatible
  - Impact on ID optimization needs to be carefully considered
- Requires several upgrades
  - RF coupler upgrade to increase power handling capability to 200 kW (now 150 kW)
  - Replacement of HOM dampers (four cavities) to improve power-handling capability
  - Modest upgrade of controls to improve stability for four-klystron operation
- Even 150 mA operation requires beamline/front-end upgrades

Front End Upgrades

Existing front-end installations at APS

Front-end Type	Max Power (kW)	Max Power Density (kW/mrad^2)
Original APS FE	6.9	198
Undulator Only FE	8.9	245
Canted FE	20	281
HHL FE	21	590

Scope of FE installations for APS-U

Type	Status	Existing	New
Original	Existing design	16	0
Undulator only	Existing design	4	0
Canted	Existing design	4	4
High Heat Load	Existing design	2	15
Long Straight Canted	New design	0	2
Short Pulse X-ray Canted	New design	0	1
Very High Heat Load	New design	0	1
Bending Magnet	Existing design	23	3

- Proposed HHL R&D essential to define limits of existing and future front-end designs

Accelerator Upgrades Target Mission Requirements

- Need for additional beamline capacity
  - 8 LSS
  - Additional canted straights
- Enhanced brightness for 25~100 keV
  - SCU, optimized IDs
  - 8 LSS
  - Higher current
  - Upgraded front ends
- Allow more demanding experiments to be performed by providing improved beam stability
- Support time-resolved studies at few-ps scale
  - Crab cavity system
  - Retention of existing fill patterns
- Significant challenges exist and are being addressed through R&D